First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

HIGH LEVEL ENGINEERING FOR STAY CABLE REPLACEMENT

Erik MELLIER[1]

[1] Freyssinet International, Velizy, France

1 INTRODUCTION

Development of cable stayed bridges really started in the 70's. At that time and until the early 90's, the stay cable specific durability requirements were not assessed properly. Many bridges built at that time now evidence early corrosion and fatigue deterioration of the cables. As the design life of these bridges is far from being reached, the cables have to be replaced.
As a leading actor on the stay cable market, Freyssinet has acquired a unique experience. General Belgrano and Zarate bridges in Argentina, Mezcala bridge in Mexico, Lanaye bridge in Belgium, Second Severn bridge in UK, Penang bridge in Malaysia are among the major cable replacement projects Freyssinet has completed over the past ten years.
This paper evidences the common problematic that was faced on these six projects, outlining the specificity and the complexity of this kind of works, but also how they are challenging for engineers.

2 EVALUATION OF THE STRUCTURE

Like any repair work, the first step is the evaluation of the real state of the structure and particularly the cables. This is to be done in several stages, beginning with a visual inspection of the structure. As the visual inspection does not automatically delivers all the information, further investigation needs to be performed, through local openings, or monitoring, and completed with a computation of structural strength in order to evaluate the actual safety in the damaged members.

2.1 Visual inspection

Visual inspection of the cable is of course the first action to be undertaken when starting with cable health assessment on a bridge. This can reveal obvious damages :
- Unusual sag of the cable, revealing the loss of tensile force in the cable,
- Heavy rust on external wire layers,
- Wire failures,
- Even cable rupture.

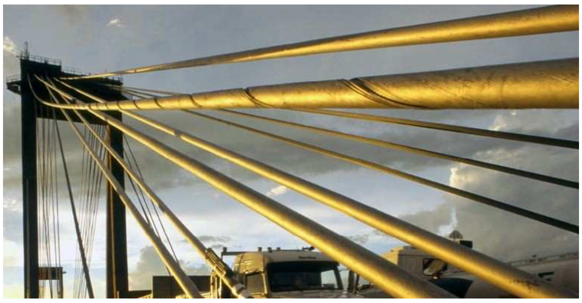

Fig 1: obvious damage on a locked coil cable, Gal Belgrano bridge, Argentina

This is of course the first, cheapest and easiest stage of the inspection. But this is not sufficient as some cables, especially parallel wire cables can experience gangrene effect. By this phenomena is called the fact that moisture penetrate into the cable through a local damage in the outer protection somewhere along the cable, travels by capillarity along the cable through the inner voids that exist in-between the wires and is trapped especially at the bottom end of the cable. Due to grout injection and the interwire friction, broken wires are reanchored by their neighbours which are overloaded and the load in the cable is not released. Hence the cable can be in very serious distress without exhibiting any visible sign of it.

Fig 2 : example of gangrene effect on a PWS cable, Zarate bridge, Argentina

A typical example is a bridge in South America where Freyssinet was called to repair one cable that had experience sudden failure and discovered that 9 other cables where very heavily corroded (up to 60% of the wires broken) without any visible evidence of that.

Hence the necessity to go beyond outer visual inspection of the cable and to open and inspect the anchorages, open locally the outer cable sheath, especially at the bottom end, next to the anchorage.

Another way to evaluate a cable health is the monitoring of the cable.

2.2 Monitoring

Monitoring the cables can be very useful when assessing a structure as it gives indications on both the current situation and the evolution of the state of the cable.

Forces can be measured by several means :

A lift-off operation with a jack gives the value at the time of the measure with a very

good precision.
A method through vibration analysis has the advantage of requiring much lighter equipments but with an accuracy that is lower.
When one wants to evaluate the force variations under different weather conditions and traffic configurations through a continuous force measurement, a load cell needs to be installed.
An acoustic monitoring is also very useful when dealing with fragile cables, either due to corrosion or bad fatigue behaviour. By automatically detecting the noise emission when a wire breaks, one can know the number and the frequence of wire breaks, their evolution with time. Through specific analysis methods developed by companies like Advitam with their Soundprint® system, it is possible to come back to the residual strength of the cables and use
it as a warning system in order to act correctly and with the adequate reactivity in case of a sudden acceleration of the cable degradation process.

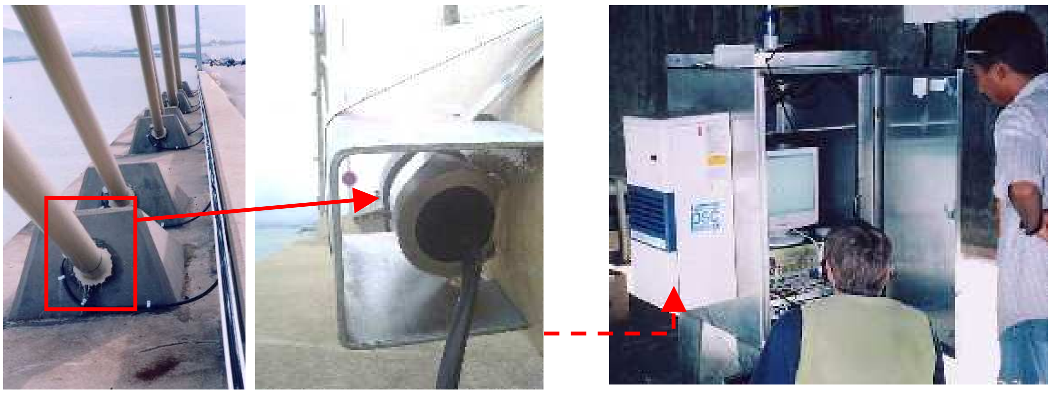

Fig 3 : Soundprint® system on Penang bridge, Malaysia

2.3 Computation

The analysis of the real state of the cable need to be completed with a proper and detailed structural analysis of the bridge in order to quantify the residual bearing capacity of the structure and any restriction on live load that might be required in most severe cases so that an adequate level of safety remains.
This was done for example for Mezcala bridge where two cables were damaged in 2007 following an accident involving a truck and a bus that burnt.

Fig 4 : structural model for the assessment of the residual bearing capacity of Mezcala bridge (Mexico) after 2007 major road accident

As part of the repair works, Freyssinet performed a computer analysis of the bridge behaviour within a few days after the accident and proved that two out of the four lanes on the bridge could remain in operation without any risk for the structure and for the users.

3 3D COMPUTER MODEL

Whenever the assessment reveals extensive loss of capacity or shortening of service life of the cable, the replacement needs to be foreseen. This is a heavy repair operation that needs to be prepared adequately.

3.1 Computer model

Replacing cables a temporary and sometimes permanent major modification of the structural behaviour of stay cable bridge. Hence it requires a detailed evaluation of the forces and stresses in the structure at all stages :

- Initial stage,
- During each stage of the replacement works,
- At the final stage.

Hence it is necessary to build a complete 3D model of the structure in order to assess properly all consequences of the works on the existing structural members.

3.2 Permanent state

First verification should focus on the structure checking in the future configuration with new stays. As the cable technology may be changed during the replacement, especially if the original one has evidenced unexpectedly rapid ageing, the stiffness of the cable may not be exactly the same. Also, as materials are stronger nowadays than they were a few decades ago, the engineer can be tempted to benefit from these progresses and install cables with stronger material and hence smaller cross section.

One has to be careful with the fact that this implies a change in the rigidity of the cables, often from stiffer to softer cables. Hence deformations under live loads are bigger and hence flexural stresses in the deck are increased compared with the original state. Three cases then :

In the best case these overstresses are acceptable and the new cables can be optimised to modern standards, provided it is demonstrated through calculation.

In the worst case, the structural design is already optimised and the structure cannot accept any overstress. Hence the new cables have to be designed in order to provide the same rigidity as the old ones, even if they don’t work at their full strength in service.

In most cases, the reality is in-between and an optimum has to be found through iterative computer analysis in order find the minimal cable cross sections that induce the maximal overstresses that are acceptable for the existing structure.

This optimisation has been necessary for the cable replacement of Penang bridge in Malaysia where original cables were very stiff as they were composed of prestressing bars encased in a thick steel tube. The Freyssinet parallel strand cables that have been installed to replace them have of course a much higher working stress (50 % of 1860

MPa). Hence cables designed for the same ultimate strength would have been too slender and have induced bending in the concrete deck that would have lead to unacceptable crack openings.

3.3 Seism

For the same reason, a complete reassessment of the seismic behaviour of the bridge is necessary if the new cables do not have the same rigidity as the old ones. A cable replacement operation may also be an opportunity to perform a seismic retrofitting of the bridge, following a seismic code revision for example.

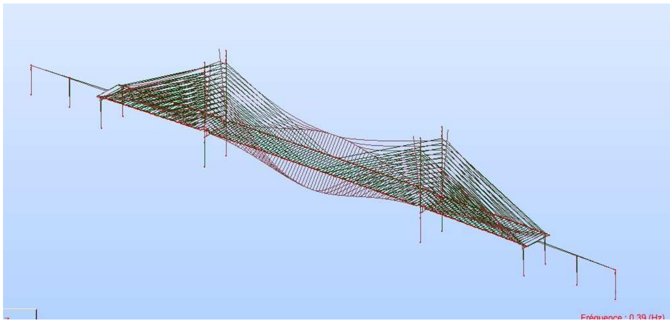

Fig 5 : reassessment of Penang bridge behaviour under seismic load

3.4 Temporary phases

Temporary phases need to be fully justified as well. The engineering work to be done is very specific to this kind of repair works, and much heavier than for a classic construction engineering.

The main reason for this is that the bridge remains in operation during the replacement works. Hence any construction stage, which corresponds to a different structural model as cables are missing and some temporary ones are added, is actually a service state and needs to be combined with traffic loads, wind loads and temperature variations.

An assumption has to be made on the stresses that are acceptable for the old cables whose capacity is known with a variable degree of reliability. A criteria that can be adopted and that seems of common sense is that the old cables should not experience tensile stresses higher than the one they have effectively experienced in a recent past. This choice of this criteria is crucial in term of the bridge structural safety during the works. It is the result of a risk analysis and a compromise : if the criteria is too low, the required structural safety is not obtained. If too high, it will have serious consequences on the studies and work complexity as it will impose the use of temporary cables stressed prior to the replacement works in order to release part of the tension in the existing cables and multiply the number of tensioning and detensionning phases in order to continuously adapt the cable tensions. Hence it has to be chosen carefully in close coordination between the owner, the engineer and the contractor.

An other aspect to be careful with is linked to the stiffness variation that was already mentioned. At the transition between old and new cables, there is a sudden variation in the stiffness of the deck support. Hence the stiffer cables, usually the old ones, attract more load than usually, which can lead to unacceptable overstresses. Once again, this can make necessary the use of temporary cables or length adjustments on existing and new cables in order to compensate this effect.

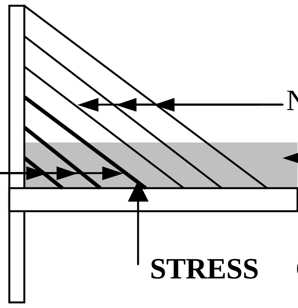

Fig 6 : mechanism of stress concentration in the longest old cable due to cable stiffness difference

4 TEMPORARY CABLES

Temporary cables are often required when replacing cables.
Different configurations happen actually :

- On old cable stayed bridges cable severance and cable replacement have not been considered as a load case at the design stage. Hence the deck and the adjacent cables are not capable of holding the loads when a cable is missing. In that case, temporary cables are necessary and need to be anchored close to the anchoring points of the dismantled cable.
- The bridge is designed for cable replacement but additional cables are still required because the actual state of the existing cables is not known with certainty and extra cables are used to limit overstresses in adjacent cables. In this case, there is more flexibility with the choice of the location of the temporary anchors.

Of course, anchoring new cables even temporarily in a structure that has not been designed for this requires engineering expertise and experience in order to minimize remaining damage on the structure.
Steel anchorages clamped on the structure with prestressing bars are often chosen as the damage on the structure is minimal. Especially coring is minimized.

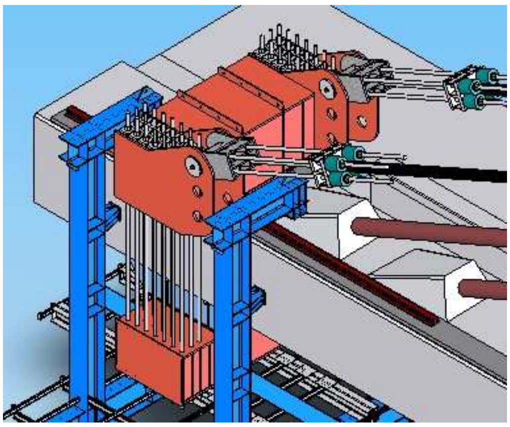

Fig 7 : clamping beam anchoring temporary cables

5 CABLE DETENSIONNING AND DISMANTLING

The detensionning of the existing cable is certainly the most critical operation as a huge amount of energy is released during the operation. Hence this needs to happen smoothly in order to :

- Limit dynamic effects that could damage the structure,
- Prevent any unexpected movement of the cable that could endanger the working personnel,
- Prevent any unsafe feeling from the bridge users.

The progressive energy release can be obtained by two procedures :

- The cable is composed of multiple tensile elements (i.e. wires) and hence each time you cut a wire you only release a small part of the total cable force. This is only applicable when the cable wires are totally independent and do not re-anchor one on the other, otherwise the energy is not released but transferred to other wires until the remaining ones fail suddenly.
- It is preferred that the entire cross section of the cable is cut at the same time and in this case it is necessary to distress the entire cable with heavy means (jacks) either before or after having cut the cable.

In any case, cutting the cable with tools that are usually used for external prestressing cables inside concrete box girders is not possible as this would induce excessive hazards for bridges users and working personnel. A picture of a cut prestressing tendon is self explanatory.

Fig 8 : controlled cable distressing in progress

6 WORK UNDER BRIDGE OPERATION AND CONSEQUENCES

Another particularity of these works is that they always occur on bridges that are long span structures and vital links for the economy and the social life of the neighbouring communities. Hence it is not an option to close the bridge during the replacement works that last several months.

Only the emergency lane and in most favourable cases one traffic lane can be closed. It means that these operations have to be accomplished with very limited space, practically a 3 meter wide strip along the bridge edge girder.

This has crucial consequences on the tools that can be used, the handling capacity, the sequencing of the works and finally the schedule.

Many specific tools need to be designed in order to work in such a specific environment for :

- Distressing the cables
- Lowering the cables to the deck
- Evacuating old cables
- Installing new cables.

On this last item, parallel strand cables offer a significant advantage as the strand by strand installation process only requires light equipment and small space on the deck.

Fig 9 : Parallel strand stay cable installation on a bridge under traffic

7 CONCLUSION

This paper has demonstrated through various examples that stay cable replacement works are highly technical works requiring specialised equipment and techniques with engineering needed at all steps of the operation. Structural assessment, construction methods and work schedule and organisation are closely interconnected and need to be studied in a very coordinated manner by teams having experience in all of these fields. This is the only way for ending with a technical solution that is durable according to modern standards, compatible with the structural capacity of the bridge, acceptable for the users in term of disturbance on the trafficability.
Regarding these concerns, parallel strand cables offer significant advantages as they are modular, require only light equipment and small space for being installed.
By extending the service life of bridges without interruption of traffic, stay cable replacement operations respond perfectly to the rising demand for sustainable solutions permitting material and cost savings.

8 REFERENCES

1. BS 5400, Part 4. 1990. CP for Design of concrete bridges.
2. EN 1993-1-11. 2007. Design of steel structures. Design of structures with tension components.
3. Freyssinet. 2007. Freyssinet HD Stay Cables.